

## Microarticle

## Influence of geometrical parameters on transmitting thermal radiation through silver halide fibers



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## A B S T R A C T

In this study, we experimentally determined the influence of fibers' geometrical parameters on the performance of fiber-optic temperature control system based on silver halide fibers at the temperatures of 295–395 K. It was revealed that the fiber diameter can affect thermal radiation transmission in the case of mismatching light beam diameters between system's optical elements and it should be taken into consideration when such systems are developed. A fiber length reduction leads to a linear increase in transmission values. We also assessed transmission losses for the fibers bent at various radii and derived some empirical equations for calibration curves. The revealed dependencies can be very useful for designing fiber-optic systems intended for remote temperature measurements and control of heating-power facilities' thermal regimes.

## Introduction

To date, there is a lack of reliable methods of temperature control for moving hard-to-reach objects such as electric motor winding, blades of gas and steam turbines and other equipment, that can be carried out without damaging the integrity of their protective casings. Although, these methods are in huge demand [1] because additional holes in casings (due to the use of multiple thermocouples in conventional systems) lead to the reduction of their strength characteristics. Therefore, the development of temperature control systems enabling minimal invasion into heat-power facilities is a relevant task. The usage of infrared fibers can help to solve this problem [2–4]. Applying temperature control systems with infrared fibers embedded, we need to take into consideration the data on temperature distortions at different fiber diameters and lengths (providing that we will achieve acceptable levels of the infrared radiation transmission), since this information is necessary on the one hand for calculating the protective casing constructional characteristics, and on the other hand for designing effective fiber-optic system for remote temperature control. We also need to know the temperature distortions caused by bends of fibers. In this connection, we need to carry out the quantitative assessment of the parameters mentioned above.

## Experimental procedure

To investigate the influence of geometrical parameters on the transmission of thermal radiation through infrared fibers, we utilized a

simple experimental setup, which is typical for endoscopic infrared thermography. The schematic diagram of the experimental setup is represented in Fig. 1.

In this study, we used a thermal camera NEC TH-9100, whose spectral range span the wavelengths from 8.0 to 14.0  $\mu\text{m}$ . A Peltier device was used as a thermal radiation source. This Peltier device allowed us to carry out measurement within the temperature range from 295 to 395 K. The considered infrared fibers were based on AgCl-AgBr solid solution crystals, namely on  $\text{AgCl}_{0.75}\text{Br}_{0.25}$  composition, which possesses the emissivity of 0.95. The fibers had different diameters (0.5, 1.12, 1.75 mm) and lengths (50, 100, 150, 200 mm), and were transparent in the wavelength range from 2.0 to 20.0  $\mu\text{m}$  [5]. The fiber samples were placed into PFTE shells to avoid fiber microbends and photoeffects. For the additional protection of the thermal camera objective from direct light exposure, we used a protective shield. The distal fiber end was located at a distance  $x = 1$  mm from the thermal radiation source, which virtually excluded heat transfer in account of thermal conduction.

## Results and discussion

## Influence of fiber diameter

We used fibers with the diameters of 0.5, 1.12, 1.75 mm and the length of 200 mm. Fig. 2(a) depicts the results of measurements as a function of temperature acquired from the proximal fiber end (the values detected by the thermal camera) and the temperature of the

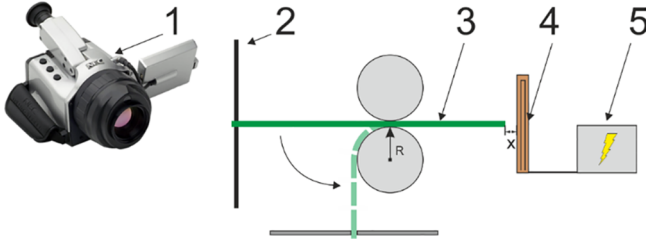
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**Fig. 1.** Schematic diagram of experimental setup: 1 – thermal camera; 2 – protective shield; 3 – infrared fiber; 4 – radiation source – thermoelectric (Peltier) device; 5 – DC current source.

thermal radiation source. The results obtained show that the fibers of 1.75 and 1.12 mm in diameter have the same thermal radiation transmission coefficients:  $k_1 = k_2 = 0.71$ . This indicates that values of transmission are not affected by fiber diameters, *ceteris paribus*. Lower temperature values, gained using  $\varnothing 0.5$  mm fiber, may be explained by mismatching between rather a small fiber diameter and a relatively large diameter of thermal camera focus spot. The latter was  $\approx 1$  mm in diameter, whereas the fiber diameter was two times smaller. Due to this, the thermal camera showed the average value between the temperature taken from the proximal fiber end and the ambient temperature resulting in a decreased transmission coefficient  $k_3 = 0.30$ .

#### Influence of fiber length

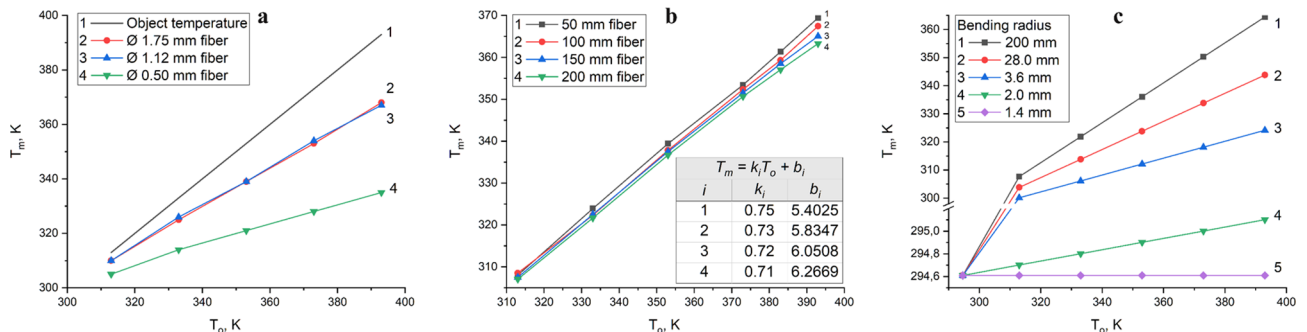
Typically, silver halide fibers possess optical losses about 0.1–0.4 dB/m @  $\lambda = 10.6 \mu\text{m}$  [6,7]. In simple cases, passing through the fiber, the light undergoes multiple reflections on the core-cladding or fiber-air interface (depending on the fiber structure), losing some power due to absorption and scattering. Therefore, shorter fiber lengths give higher outgoing power. For the quantitative evaluation of this dependence, we used the cut-back technique [8].

The chosen fibers had a diameter of  $d = 1.75$  mm and lengths of 50, 100, 150, and 200 mm. Fig. 2(b) shows the experimental results for the Peltier device over the temperature region of 295–395 K. It was found that the fiber length directly influences infrared radiation loss. The data in the figure correspond to the optical losses of  $0.35 \pm 0.05$  dB/m what is in good agreement with the results obtained previously by FTIR spectroscopy (about 0.4 dB/m for single-layer silver halide fibers within the spectral range of 6–15  $\mu\text{m}$  [6]).

We obtained the empirical equations for all the plotted calibration lines. Their general form is represented below:

$$T_o = \frac{(T_m - T_r)}{\lg(\alpha)} + T_r, \quad (1)$$

where  $T_o$  – object's temperature,  $T_m$  – temperature measured by means of the fiber-optic system,  $T_r$  – ambient temperature,  $\alpha$  – the slope of linear function  $T_m(T_o)$  corresponding to fiber transmission.



**Fig. 2.** Temperature measured onto the proximal fiber end  $T_m$  in comparison with Peltier device's real temperature  $T_o$ : (a) at various fiber diameters and a length of 200 mm; (b) at various fiber lengths and a diameter of 1.75 mm; (c) at various fiber bend radii, a length of 200 mm, and a diameter of 1.12 mm.

**Table 1**

Bending radii and equation coefficients for the obtained graphs in the studied cases.

Bend radius $R$ , mm	200.0	28.0	3.6	2.0	1.4
Linear function slope $\alpha$ , °	35.4	26.6	16.7	0.3	0.0
$k_i$ ( $i = 1 \div 4$ )	0.710	0.500	0.300	0.005	0.00
$b_i$ ( $i = 1 \div 4$ )	6.266	10.805	15.127	21.507	21.609

#### Influence of fiber bend radius

When the light passes through a bent fiber segment, it can leak through the fiber lateral surface to some extent due to attenuated total internal reflection. Once a certain bend radius is reached, the bending losses rise very quickly. This radius is usually called a critical one and it may be calculated by the following formula [9]:

$$R_{cr} = \frac{4a}{\left(\cos^{-1} \frac{n_{clad}}{n_{core}}\right)^2}, \quad (2)$$

where  $a$  – fiber radius,  $n_{clad}$ ,  $n_{core}$  – refractive indices of fiber cladding and core, respectively. For our investigations, we used single-layer fiber with a length of 200 mm and a diameter of 1.12 mm. It possessed a refractive index of 2.122 [10]. Its critical bending radius was computed as 1.78 mm.

We studied the impact of fiber bending on the transmission of thermal radiation in order to find acceptable fiber bend radii enabling the maintenance of negligible bending losses. Fiber bend radii of 1.4, 2.0, 3.6, 28.0, and 200 mm were used for the experiment. The curvature angle was  $90^\circ$  relative to the straight position. The obtained temperature values are given in Fig. 2(c). Obviously, when the fibers are bent to radii larger than the critical one, the transmitted light completely leaks out of the fiber lateral surface what is clearly seen in Figure. When the bending radius equals to 200 mm, it is more 100 times larger than the fiber diameter, which results in bending losses that can be neglected according to an approximate rule given in Ref. [11]. Basing on the empirical data, the slopes of linear functions were obtained (see Table 1).

Thus, the dependence of determined temperature on fiber diameter was not revealed, except the case, there was a limitation connected to the lens resolution of the thermal camera. It can be eliminated by using lenses with better resolution. It was found that a fiber length reduction leads to a linear increase in thermal radiation transmission values within the range of 295–395 K. These values were in good agreement with the transmission losses obtained earlier by authors. We also measured temperature distortions caused by bending fibers. Moreover, we defined the calibration coefficients of the experimental fiber-optic temperature control system.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rinp.2020.102994>.

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